23019

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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : B32B 5/08, 5/16, E04C 3/26, 3/29

A1

(11) International Publication Number: WO 96/00653

(43) International Publication Date: 11 January 1996 (11.01.96)

(21) International Application Number: PCT/US95/08329

(22) International Filing Date: 29 June 1995 (29.06.95)

(30) Priority Data:
08/269,004 30 June 1994 (30.06.94) US

(60) Parent Application or Grant
(63) Related by Continuation
US 08/269,004 (CIP)
Filed on 30 June 1994 (30.06.94)

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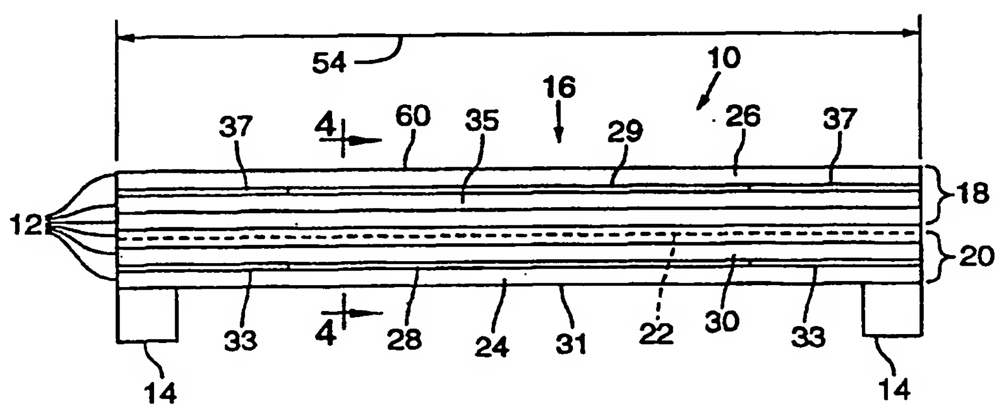
(81) Designated States: AM, AT, AU, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DK, EE, ES, FI, GB, GE, HU, IS, JP, KE, KG, KP, KR, KZ, LK, LR, LT, LU, LV, MD, MG, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TT, UA, UG, US, UZ, VN, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG), ARIPO patent (KE, MW, SD, SZ, UG).

Published
With international search report.

(54) Title: METHOD OF MANUFACTURING WOOD STRUCTURAL MEMBER WITH SYNTHETIC FIBER REINFORCEMEMT



(57) Abstract

An elongated wood structural member or beam (10) for bearing predetermined loads (16) transverse to the lengths (54) of the members preferably includes multiple elongate wood segments (12) bonded together with their lengths generally aligned with the beam length as in a glue-laminated members. The predetermined load corresponds to a resisting moment that produces compressive and tensile stresses in the structural member in respective compression (18) and tension (20) portions of the beam on opposite sides of a neutral axis (22). A synthetic tension reinforcement (28) having multiple synthetic fiber strands held within a resin matrix is adhered to at least one of the wood segments in the tension portion of the structural member and is selected to be substantially capable of bearing the tensile stress produced by the resisting moment and cooperates with the wood segments to position the neutral axis within the beam. As a result, the width and depth of the structural member and relative positions of the neutral axis and reinforcement (29) may be selected to establish a compression portion of the structural member in which compressive stress from the resisting moment does not exceed a predetermined maximum compressive stress.

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METHOD OF MANUFACTURING WOOD STRUCTURAL MEMBER WITH SYNTHETIC FIBER REINFORCEMENT

Related Application

This application is a continuation-in-part of copending U.S. patent application No. 08/269,004, which is a continuation-in-part of U.S. patent application No. 08/037,580, filed March 24, 1993, now U.S. Patent 5,362,545, for "Aligned Fiber Reinforcement Panel for Structural Wood Members."

Technical Field

The present invention relates to wood structural members reinforced with fiber panels and, in particular, to a method of designing and manufacturing such wood structural members so that they will meet predetermined load capabilities.

Background of the Invention

Beams, trusses, joists, and columns are the typical structural members that support the weight or loads of structures, including buildings and bridges. Structural members may be manufactured from a variety of materials, including steel, concrete, and wood, according to the structure design, environment, and cost.

Wood structural members are now typically manufactured from multiple wood segments that are bonded together, such as glue-laminated members, laminated veneer lumber, parallel strand lumber, and I-beams. These

manufactured wood structural members have replaced sawn lumber or timbers because the former has higher design limits resulting from better inspection and manufacturing controls. Wood is a desirable material for use in many structural members in part because of its strength for a given weight, appearance, cyclic load response, and fire resistance.

In any application, a load subjects a structural member to compressive and tensile stresses, which correspond to the respective compacting and elongating forces induced by the load in opposite sides of the member. A neutral plane separates the portions of the member under compression and tension. The structural member must be capable of bearing the compressive and tensile stresses without undergoing a level of strain that would create a danger of failure.

Wood structural members have generally similar stress characteristics in tension and compression. A characteristic of wood structural members under extreme loads, however, is that ultimate failure in bending is usually initiated by failure in the tension portion due to localized defects such as knots, slope of grain, or finger joints. When one portion in tension fails, the stress it was bearing is transferred to other portions in tension. This may cause a chain reaction of failure. By comparison, the compression portion can withstand higher applied loads because even a failed fiber may bear some stress in compression. Therefore, a lamina in compression is comparatively very resistant to chain reaction failure. Accordingly, the conventional practice is to manufacture wood structural members to have adequate (with a margin of safety) tension portions to bear the required tensile stresses in bending.

Summary of the Invention

An object of the present invention is, therefore, to provide wood structural members with improved stress-resisting capabilities.

Another object of this invention is to provide such wood structural members with tensile and compressive portions adapted to stresses imposed by a predetermined load.

A further object of this invention is to provide a method of manufacturing such wood structural members.

The present invention includes wood structural members, particularly beams, for bearing predetermined loads. A wood structural member of a preferred embodiment includes multiple wood segments bonded together with their grain generally aligned together as in glue-laminated members, laminated veneer lumber, parallel strand lumber, and I-beams. The predetermined load creates a resisting moment that produces compressive and tensile stresses in the structural member in respective compression and tension portions of the beam on opposite sides of a neutral axis.

A synthetic reinforcement having at least one layer of resin-encased fibers is adhered to at least one of the wood segments in the tension portion of the structural member. The synthetic tension reinforcement is selected to be substantially capable of bearing the tensile stress produced by the resisting moment. In addition, this reinforcement shifts the neutral axis upwards. As a result, the width and depth of the structural member and type and thickness of the reinforcement may be selected to prevent the compression stress in the compression portion from exceeding a predetermined level. A synthetic compression reinforcement may also be used to bolster the compression resistance of the compression zone.

Frequently, wood laminae used to make up a laminate are themselves made up of segments of wood aligned together and joined with interdigitated or "finger" joints. These finger joints frequently present a failure mechanism that is activated at a load lighter than that necessary to cause compression failure. In these instances, the member construction is chosen to prevent finger joint failure.

Since the yielding of wood fibers in the compression portion does not initiate an immediate chain reaction failure of the member, larger applied loads can be supported than with an unreinforced beam of equal size. Therefore, with an appropriate tension reinforcement, the dimensions of the wood structural member can be reduced. Less wood or lower grade wood may be used as part of a member having strength to bear a structural load. Because heretofore these inexpensive lower grades of wood could generally not be used for challenging structural purposes, their use reduces the cost of the member. In many cases the reduction in cost allows the wood member to successfully compete with equivalent steel and concrete members.

The present invention also includes a method of manufacturing such reinforced structural members. In a preferred embodiment, the method includes theoretically modifying an initial member depth and width and synthetic reinforcement thickness and length until a calculated maximum resisting moment is sufficient to match a predetermined load moment. The beam design may then be further modified to meet shear strength, stiffness, combined axial bending, and fire resistance requirements. After the design is complete, the beam is produced in accordance with the design.

Additional objects and advantages of this invention will be apparent from the following detailed

description of preferred embodiments thereof which proceeds with reference to the accompanying drawings.

Brief Description of the Drawings

Fig. 1 is an elevation view of an exemplary laminated wood beam having synthetic fiber reinforcement according to the present invention.

Fig. 2 is a perspective view of a section of a portion of a synthetic fiber reinforcement with a portion cut-away to show the alignment and orientation of fibers in the reinforcement.

Fig. 3 is a flow diagram showing a process for manufacturing the laminated wood beam of Fig. 1 so that both tensile and compressive portions are adapted to the stresses imposed by a predetermined load.

Fig. 4 is a sectional end view of the wood laminated beam along line 4--4 in Fig. 1.

Detailed Description of Preferred Embodiments

Fig. 1 shows a glue laminated wood structural member 10 having multiple wood laminae 12 that are bonded together and may be elongate boards. In this configuration, wood beam 10 is configured as glue-laminated timber. Although this is a preferred configuration of wood structural member 10, the following description is similarly applicable to other wood structural members, including laminated veneer lumber, parallel strand lumber, and wood I-beams.

A typical structural use of wood structural member 10 is to span and to bear a load above an otherwise open region. As a simplified, exemplary representation of such use, wood structural member 10 is shown with its ends supported by a pair of blocks 14 and bearing a point load 16 midway between blocks 14. The product of the force corresponding to load 16 and its distance from one of blocks 14 represents a moment applied to wood structure member 10. The load moment is balanced or equaled by a

resisting moment that creates compressive and tensile stresses in wood beam 10 in respective compression and tension portions 18 and 20 of structural member 10 on opposite sides of a neutral axis 22.

Under the conditions represented in Fig. 1, a lowermost lamina 24 is subjected to a substantially pure tensile stress, and an uppermost lamina 26 is subjected to a substantially pure compressive stress. To increase the tensile load-bearing capacity of wood structural member 10, at least one layer of synthetic tension reinforcement 28 is adhered between lowermost lamina 24 and a next adjacent lamina 30 or, alternatively, to only the outer surface 31 of lowermost lamina 24. A compression reinforcement 29 may also be included, attached either to the uppermost surface 60 of the uppermost lamina 26 or between the uppermost lamina 26 and a next adjacent lamina 35.

According to the present invention, synthetic tension reinforcement 28 is substantially capable of bearing the tensile stress produced by the resisting moment in wood structural member 10. Synthetic tension reinforcement 28 is generally centered about load 16 and preferably extends along about two-fifths to three-fifths the length of wood structural member 10, depending on load 16. Two tension wood spacers 33 are positioned at opposite ends of synthetic tension reinforcement 28 between laminae 24 and 30 to maintain a uniform separation between them. In similar manner, compression wood spacers 37 are positioned at opposite ends of compression reinforcement 29 between laminae 26 and 35. Synthetic tension reinforcement 28, being substantially capable of bearing the tensile stress produced by the resisting moment, allows wood structural member 10 to have a width 32 and a depth 34 selected according to either the compressive stress in the compression portion of the

structural member, or finger joint strength as described below in greater detail.

Fig. 2 is an enlarged perspective view of one layer of preferred synthetic tension reinforcement 28 having a large number of synthetic fibers 36 that are arranged parallel to one another and aligned with the length of synthetic tension reinforcement 28. A resin material 38 surrounds and extends into the interstices between synthetic fibers 36 to maintain them in their arrangement and alignment. To facilitate its adhesion to laminae 24 and 30, synthetic tension reinforcement 28 preferably has many thousands of fiber ends emanating from its surface to aid in its adhesion with other members.

The parallel arrangement and longitudinal alignment of the fibers 36 provides synthetic tension reinforcement 28 with maximal strength.

Suitable for use as synthetic fibers 36 are aramid fibers, which are commercially available from E.I. DuPont de Nemours & Co. of Delaware under the trademark "KEVLAR," and high modulus polyethylene, which is available under the trademark "SPECTRA" from Allied Fibers of Allied Signal, Petersburg, Virginia. A preferred grade of synthetic fibers 36 is an aramid fiber available as "KEVLAR 49." Resin material 38 used in fabrication of synthetic tension reinforcement 28 is preferably an epoxy resin, but could alternatively be other resins such as polyester, vinyl ester, phenolic resins, polyimides, polystyrylpyridine (PSP), or thermoplastic resins such as polyethylene terephthalate (PET) and nylon-66.

Synthetic fibers 36 preferably have a modulus of elasticity in tension that is relatively high. For example, synthetic fibers 36 of Kevlar™ have a modulus of elasticity in tension of about 18 x 10^6 psi (124,000 MPa). Synthetic reinforcement 28 comprising about 60 percent synthetic fibers 36 to 40 percent resin material 38 (by

volume) has a modulus of elasticity in tension of about 11 x 10^6 psi (75,900 MPa).

Suitable for use as synthetic compression fibers 44 are commercially available carbon fibers, which have a modulus of elasticity in compression of about 30 x 10^6 psi (206,900 MPa). Synthetic compression reinforcement 29 comprising about 60 percent synthetic fibers 44 to 40 percent resin material 38 (by volume) has a modulus of elasticity in compression of about 18 x 10^6 psi (124,000 MPa). Resin material 38 used in fabrication of tension reinforcement 28 and compression reinforcement 29 is preferably an epoxy resin, but could alternatively be other resins such as polyester, vinyl ester, phenolic resins, polyimides, polystyrylpyridine (PSP), or thermoplastic resins such as polyethylene terephthalate (PET) and nylon-66.

Fig. 3 is a flow diagram showing a process 50 for manufacturing wood structural member 10 so that tensile and compressive portions are adapted to the stresses imposed by load 16.

For purposes of illustration, process 50 will be described with reference to the simplified representation of structural use of wood structural member 10 shown in Fig. 1. It will be appreciated, however, that this description does not reflect a limitation on the structural use of member 10 or process 50. Wood structural member 10 and process 50 could alternatively be used in a wide variety of other load and support configurations, including distributed and nonperpendicular loads and asymmetric or cantilevered support configurations.

Prior to beginning design and manufacturing process 50, it is necessary to take a preliminary evaluation of what laminated structure one wishes to build, determine the loads which will be applied to the

member, the species of wood of which the member will be constructed and the type of synthetic reinforcement or reinforcements to be included in the member (process block 52). The process of determining many of these quantities is old in the art and familiar to skilled practitioners. As for the use of synthetic reinforcements, a few rules may guide the designer.

If the member is a simple load bearing member without an exacting stiffness requirement, a tension reinforcement will generally be adequate. If there is an exacting stiffness requirement, then a compression reinforcement is also required. Further, if a fire rating is necessary, the reinforcement will be placed between two laminae and should be made of resin encased carbon, fiberglass or aramid fibers. Otherwise, it will be placed on the lowermost portion of the lowermost lamina. Final length is determined by process 50.

Process block 56 indicates that a starting width and depth and a tension reinforcement thickness and length have been selected from respective predetermined sets of working structure widths, working structure depths, and working tension reinforcements. Typically the process is started with a value for each one of these quantities that a skilled wood member designer knows is smaller than what will be needed to support the predetermined load or is the minimum available from the predetermined sets. Typically the thinnest synthetic reinforcement would be 0.07 inch (1.8 mm) thick. This value would be chosen as the initial value of reinforcement thickness to start process 50. The initial value for the tension reinforcement is set at one-half the length of the member.

The set of working structure widths correspond to predetermined widths of wood structural member 10. The set of working structure depths corresponds to the number of laminae 12 in wood structural member 10 (multiplied by

the thickness of each such laminae). The working tension reinforcements correspond to the number of layers, position, and length of tension reinforcement 28.

Calculation of Neutral Axis

Process block 58 indicates that the location of neutral axis 22 between compression and tension portions 18 and 20 is calculated. Referring to Fig. 4, which is a sectional end view of wood structural members 10 along the lines 4--4 in Fig. 1, the location of neutral axis 22 may be calculated as a distance "a" from compression surface 60 as:

Tension reinforced laminated member

$$a = \frac{d\sqrt{n}}{1 + \sqrt{n}} + M_t - N_t$$

Compression and tension reinforced laminated member

$$a = \frac{d\sqrt{n}}{1 + \sqrt{n}} + M_t + N_t - M_c - N_c$$

Where

a = Distance to neutral axis (NA) from top of beam (inches)

d = Depth of beam (inches)

c = Distance from NA to bottom extreme fiber in tension of beam in bending (inches)

n = Modular ratio of wood Modulus of Elasticity (MOE_{wt}) in pure tension to Modulus of Elasticity (MOE_{wc}) wood in pure compression

n Values for Wood

Douglas-fir	All Grades	1.06
Hem-fir	L-1D	1.06
	L-1	1.08
	L-2	1.10
	L-3	1.10
Western Woods	N-1	1.06
	N-2	1.08
	N-3	1.10

Southern Yellow Pine	All Grades	1.06
All E-rated Material		1.06

$$M_t = n(n' - 1)^{0.8} \quad T_{rt}$$

Where

M_t = Adjustment value for reinforcement in tension zone (inches)

n' = Modular ratio of FiRP™ Reinforcement Modulus of Elasticity (MOE_{rt}) in tension to MOE_{wc}

T_{rt} = Total thickness of reinforcement in tension zone (assume glueline thickness of zero for each FiRP™ Panel) (inches)

$$N_t = nR_t \ (n' - 1) \ T_{rt} \ / \ a'$$

Where

N_t = Adjustment value for bumper layer in tension zone (inches)

R_t = Distance from center line of tension reinforcement group (include a glueline for each FiRP™ Panel of .002") to outer edge of beam on tension side (inches)

$$a' = \frac{d \quad \sqrt{n}}{1 + \sqrt{n}}$$

$$M_c = n \ (n'' - 1)^{0.8} \ T_{rc}$$

Where

M_c = Adjustment value for reinforcement in compression zone (inches)

n'' = Modular ratio of compression reinforcement Modulus of Elasticity (MOE_{rc}) in compression to MOE_{wc}

T_{rc} = Total thickness of reinforcement in compression zone assume glueline thickness of zero for each FiRP™ Panel (inches))

$$N_c = nR_c \quad (n'' - 1) \ T_{rc} \ /a'$$

Where

N_c = Adjustment value for bumper layer in compression zone (inches)

R_c = Distance from centerline of compression reinforcement group (include a glueline for each FiRP™ Panel of 0.002 inch) to outer edge of beam on compression side (inches)

The modulus of elasticity in tension $MOE(r)_t$ of tension reinforcement 28 comprising Kevlar™ 49 is 11 x 10^6 psi (75,900 MPa). The modulus of elasticity of wood in bending $MOE(w)_b$ of an unreinforced member may be calculated as the average of the moduli of elasticity of wood in tension and compression ($MOE(w)_t$ and $MOE(w)_c$), which are commonly tabulated values for $MOE(w)_b$. Exemplary thicknesses t_r of tension reinforcement 28 are 0.066, 0.090, and 0.146 inch (1.68, 2.29, and 3.71 mm).

Maximum Safe Resisting Moment

Decision block 70 determines whether the maximum safe resisting moment, M_r, is larger than the load moment. The value of M_r is calculated as follows:

$$M_r = (C \cdot z \cdot FJQ/FJD) \cdot Cl \cdot Cmt \cdot Cd \cdot Ct/12$$

Where

M_r = Maximum safe resisting moment (ft.-lbs.)

C = $F'c \cdot a \cdot b$

FJQ/FJD is limited to a maximum value of 2.0

Where

$$F'c = Fc \cdot Cd \cdot Cm \cdot Ct \cdot (Cl \text{ or } Cv, \text{ whichever is less})$$

Where

$F'c$ = Maximum allowable design stress in compression parallel to grain (psi), adjusted for service conditions; well known in the art

Fc = Allowable design stress in compression parallel to grain (psi), adjusted for

service conditions; well known in the art

Cd = Load duration factor

Cmt = Wet service factor for bending and extreme fiber stress in tension zone; well known in the art

Ct = Temperature factor

Cv = Volume factor

Cl = Beam stability factor; well known in the art

NOTE:

1. The lower of Cv or Cl is used.
2. In compression zone reinforced beams, the reinforcement is ignored in calculation of resisting moment.

$$z = a/2 + g$$

Where

z = Moment arm, in inches (see Fig. 4)

g = Distance from NA to centerline of reinforcement in tension zone (inches)

$$FJD = \frac{F'c \cdot a \cdot FS_c}{(n' \cdot T_{rt}) + 0.5 \cdot c} \text{ (psi)}$$

Where

FJD = Finger joint design stress level (psi)

FJQ = Finger joint qualification stress level provided by manufacturer

FS_c = Safety factor in compression = 2.5 when member has compression and tension reinforcement; = 1.9 when member has only tension reinforcement

The calculation of the load moment is old and well known in the art. If the resisting moment, M_r, is greater than the load moment, the load bearing criteria is met and the method progresses to decision block 78. Otherwise, the method proceeds to decision block 72.

Decision block 72 represents an inquiry as to

whether the design value maximum, in this case resisting moment M_r, is greater than 70% of required value, in this case the load moment. If so, decision block 72 proceeds to process block 74. If not, decision block 70 proceeds to process block 76.

Process block 74 indicates that whenever the resisting moment M_r is greater than 70% of the load moment, the depth of wood structural member 10 is incrementally increased from the set of working structure depths and the method is returned to process block 58.

Process block 76 indicates that whenever the resisting moment M_r is less than 70% of the load moment, the initial width is incrementally increased from the set of working structure widths and process block 76 returns to process block 58.

Test for Stiffness

Decision block 78 determines whether member stiffness meets the requirement. This quantity is evaluated as follows:

Member stiffness = $MOE_{roxx}\ I_r$

MOE_{roxx} = Modulus of Elasticity in bending x-x direction (psi)

NOTE: For MOE_{royy} (y-y direction) multiply by 0.95

$$
\begin{aligned}
I_r = \ & b\cdot(d - BT_c - BT_t - T_{rt} - T_{rc})^3/12 \\
& + b\cdot T_{rt}{}^3\cdot n'/12 + b\cdot T_{rc}{}^3\cdot n''/12 \\
& + b\cdot BT_c{}^3/12 + b\cdot BT_t{}^3/12 \\
& + b\cdot T_{rt}\cdot n'\cdot((d - a) - BT_t + T_{rt}/2)^2 \\
& + b\cdot T_{rc}\cdot n''\cdot((d - a) - BT_c + T_{rc}/2)^2 \\
& + BT_t\cdot b\cdot(c - BT_t/2)^2 + BT_c\cdot b\cdot(a - BT_c/2)^2 \\
& + ((b\cdot(d - T_{rc} - T_{rt} - BT_t - BT_c)) \\
& \cdot(((d - T_{rc} - T_{rt} - BT_c - BT_t)/2 \\
& + BT_c + T_{rc}) - a)^2)
\end{aligned}
$$

Where

b = Width of beam (inches) (See Fig. 4)

BT_t = Bumper layer thickness (inches) tension zone

BT_c = Bumper layer thickness (inches) compression zone

NOTES: MOE_{roxx} values for various wood lamina grade and species are listed below. These values are the average base MOE_{roxx} derived from extensive reinforced beam tests. They reflect major improvements in composite stiffness as a result of the reinforcements averaging effect on composite Modulus of Elasticity; they should not be used for unreinforced glulams.

They represent average values for use with various percentages of reinforcement and types of reinforcement as well as lengths and sizes. All service

factors generally considered relevant to Modulus of Elasticity apply to MOE_{roxx}.

Table 1

MOE_{roxx} Values for Various Lamina Species and Minimum Grades

($x\ 10^6$ psi)

Minimum Grade	Species	FiRP™ Design MOEroxx
2.3E-1/6	D-fir	2.60
L-1	D-fir	2.20
L-2	D-fir	2.20
L-3	D-fir	2.20
2.3E-1/6	E-SP	2.60
L-1	Hem-fir	2.00
L-1D	Hem-fir	2.00
L-2	Hem-fir	2.00
L-3	Hem-fir	2.40
N-1D	SP	2.00
N-2D	SP	1.80
N-2M	SP	1.90
2.1E-1/6	WW	1.90
N-1	WW	1.60
N-2	WW	1.50
N-3	WW	1.60

NOTE: The above values are averages for various sizes, lengths, types of reinforcement, and concentrations of reinforcement as well as partial length applications.

Decision block 78 compares this stiffness with a predetermined stiffness requirement. If block 78 determines that the structural member is insufficiently stiff, operation proceeds to block 72 where it is determined whether to increase member depth or width. After this process, block 78 again determines whether the structural member is sufficiently stiff.

Shear Strength Requirement Test

When the stiffness test is passed, the process proceeds to decision block 80 where it is determined whether member meets the shear strength requirement.

Shear strength is computed as follows:

$$V_r = F'_v \cdot 2 \cdot A/3$$

Where

V_r = Resisting horizontal shear strength (lbs)

A = Cross sectional area (inches^2)

$F'_v = F_{rv} \cdot C_d \cdot C_m \cdot C_t$

Where

F'_v = Allowable horizontal shear stress (psi) adjusted for service conditions, NDS-91

F_{rv} = Allowable design horizontal shear stress resistance of FiRP™ Glulam (psi)

$F_{rv} = D_v + (20 \cdot LN(x))$

Where

x = % reinforcement by cross section (total tension and compression). See Table 2 for maximum allowable F_{rv} values.

D_v = 273.55 for Douglas-fir, Southern Yellow Pine, and Hem-Fir member wood combinations; 228.55 for Western Woods.

NOTE: The values given by the above equation are capped by the maximum values set out in Table 2 below. Also, the minimum values from the table establish the lowest possible values. Moreover, the % reinforcement by cross section is limited to between 0.15% to 4.0%. Limit % reinforcement by cross section to 2.0 % for tension and 2.0 % for compression in calculations of x. For unreinforced portions of laminated member uses F_{rvb} base values from Table 2.

Table 2

FiRP™ Glulam Allowable Design Horizontal Shear Values

Minimum Grade	Species	Base F_{rvb} (psi)	Maximum Allowable F_{rv} (psi)
2.3E-1/6	D-fir	230	270
L-1	D-fir	230	270

L-2	D-fir	230	270
L-3	D-fir	230	270
2.3E-1/6	SP	230	270
L-1	Hem-fir	230	270
L-1D	Hem-fir	230	270
L-2	Hem-fir	230	270
L-3	Hem-fir	230	270
N-1D	SP	230	270
N-2D	SP	230	270
N-2M	SP	230	270
2.1E-1/6	WW	185	225
N-1	WW	185	225
N-2	WW	185	225
N-3	WW	185	225

If the shear strength calculated for wood structural member 10 is less than that specified, the process goes to decision block 72 and either member depth or width is increased. Process 50 is then repeated, staring with block 58, and the shear strength is again calculated and compared to the allowable specification. These iterations may be repeated until wood structural member 10 has sufficient shear strength to meet the allowable specification. When the shear strength is adequate, the process proceeds to decision block 82.

Bending and Axial Stress Requirement

Decision box 82 evaluates whether the requirement for member performance under simultaneous bending and axial stress is met. To meet this requirement the following inequality should be satisfied for members in tension:

$$f_t/F_t' + M_a/M_r\cdot \leq 1.0$$

Members in compression should meet this alternative inequality, which is explained further in the following subsection:

$$[f_c/F'_c]^2 + (M_a/M_r ** (1 - (f_c/F_{cE1})))$$
$$+ (f_{b2}/F_{b2}'\cdot(1 - (f_c/F_{cE2}) - (f_{b1}/F_{bE})^2)) \leq 1$$

If either inequality is not satisfied, the method proceeds to decision block 72 for either widening

or deepening the member. Otherwise, the method progresses to decision block 84.

With respect to the tension equation:

f_t = Applied tension stress parallel to grain (psi)

$F_t' = F_t \cdot Cm \cdot Cd \cdot Ct$

Where

F_t' = Allowable design tension parallel to grain (psi) stress value, with well known service factors applied

F_t = Allowable design tension parallel to grain (psi) stress value; well known in the art

M_a = Applied moment (ft.-lbs.)

$M_r^* = (C \cdot z \cdot FJQ/(FJD + f_t)) \cdot Cl \cdot Cmc \cdot Cd \cdot Ct/12$

Where

M_r^* = Allowable design resisting moment including effects of axial tensile stress (ft.-lbs.)

The requirement for a member in compression is repeated here:

$$[f_c/F'_c]^2 + (M_a/M_r ** (1 - (f_c/F_{cE1})))$$
$$+ (f_{b2}/F_{b2}' \cdot (1 - (f_c/F_{cE2}) - (f_{b1}/F_{bE})^2)) \leq 1$$

Where

f_c = Applied compressive stress parallel to grain (psi)

In which

$f_c < F_{cE1} = K_{cE} \cdot MOE'_{roxx}/(l_{e1}/d_1)^2$

for either uniaxial or biaxial bending

Where

F_{cE1} = Critical buckling design value for compression member in plane of lateral support (psi)(load perpendicular to narrow face)

K_{cE} = 0.418

$MOE'_{roxx} = MOE_{roxx} \cdot Cm \cdot Ct$

Where

MOE'_{roxx} = FiRP™ Glulam x-x bending Modulus of Elasticity value adjusted for service (psi). Adjustment values found in NDS-91.

l_{e1} = Effective length of bending member span, inches, in x-x direction.

d_1 = Depth in inches in x-x direction.

f_{b2} = Applied bending stress, psi, in y-y direction.

F_{b2}' = Allowable design bending stress, psi, in y-y direction

In which

$f_c < F_{cE2} = K_{cE}\ MOE'_{royy}/(l_{e2}/d_2)^2$ for biaxial bending

and

$f_{b1} < F_{bE} = K_{bE}\ MOE'_{roxx}/(R_B)^2$ for biaxial bending

Where

$MOE'_{royy} = MOE_{royy} \cdot Cm \cdot Ct$

Where

MOE'_{royy} = Modulus of Elasticity of beam in y-y bending, psi, service adjusted according to NDS-91.

K_{cE} = 0.609

l_{e2} = Effective length of bending member span, inches, in y-y direction.

d_2 = Depth in inches in y-y direction.

F_{cE2} = Reference allowable compression stress parallel to grain in y-y direction (psi). Critical buckling design value for compression member in planes of lateral support.

$R_B = (l_{e1} \cdot d_1/b_1^{2})^{0.5}$

Where

R_B = Slenderness ratio of bending member in x-x direction.

f_{b1} = Applied bending tensile stress in the tension zone, psi, in x-x direction.

$$f_{b1} = \frac{Ma \cdot c}{Ir}$$

$$F_b^* = M_r c \, / \, I_r$$

Where

F_b^* = Transformed equivalent allowable tensile stress in tension zone in bending, psi, in x-x direction.

F_{bE} = Critical buckling design value, psi, for bending members in x-x direction.

$$M_r^{**} = (c \cdot z \cdot FJQ/(FJD - f_c))/12$$

Where

M_r^{**} = Resisting moment including effects of axial compression stress (ft.-lbs.)

The lateral stability factor, Cl, for beams in bending is defined as follows:

$$Cl = (1 + (F_{bE}/F_b^*))/1.9 - (((1 + (F_{bE}/F_b^*))/1.9)^2 - ((F_{bE}/F_b^*)/.95))^{0.5}$$

NOTE: The beam stability factor, Cl, applies when width and depth ratios exceed allowable values, e.g. for $d \leq b$, Cl = 1.0.

Length of Synthetic Reinforcement

Decision block 84 determines whether the length of the synthetic tension reinforcement is adequate. To do this, the maximum safe resisting cutoff moment is calculated. This is a constant across the length of the member. The load moment varies across the length of the member, reaching its maximum at the center. The load moment must be less than the maximum safe resisting cutoff moment value at the extremes of the synthetic tension reinforcement. If it is not, the method proceeds to process block 85 where the reinforcement is lengthened.

Process block 85 returns to block 84 for another test. The load moment may be found according to well known techniques. The safe resisting moment may be found as follows:

$$M_{ro} = (F'_b \cdot S_o/Sr)/12$$

Where

M_{ro} = Resisting cutoff moment (ft.-lbs.)

F'_b = $F_b \cdot Cm \cdot Cd \cdot Ct \cdot$ (Cl or Cv, whichever is less)

Where

F'_b = Allowable design stress extreme fiber in tension zone in bending adjusted for service conditions (psi).

F_b = Allowable design stress extreme fiber in tension zone in bending (psi); well known in the art.

S_o = $b \cdot (d)^2/6$

Where

S_o = Section modulus at end of reinforcement in unreinforced portion of beam (inches^3).

Sr = $1.538\ T_{rt} + 1.6$

Where

Sr = Stress raiser factor

NOTE: SR = 1 for $T_{rt} \leq 0.15$ inch thick.

NOTE: Add 1 foot of length to each end of FiRP™ Panel upon completion of partial length requirements for safety. When proper length is found the process continues simultaneously to the maximum allowable ending and axial is found as follows.

<u>Test of Reinforcement Strength</u>

Decision block 86 represents an inquiry as to whether tension reinforcement 28 is substantially capable of bearing the applied load in tension without exceeding a strain limit. Likewise it is determined if compression reinforcement is substantially capable of bearing the

applied load in compression without exceeding a strain limit. The inequalities which should be satisfied for the member to pass this test follow:

Tension Reinforcement

$ST_{rt} < ST_{rt}$ Allowable

Where

$ST_{rt} = (C - (c \cdot b \cdot .5 \cdot FJQ/2.1))/(T_{rt} \cdot b)$

ST_{rt} = Axial tensile stress in tension reinforcement

ST_{rt} Allowable Allowable axial tensile stress tension reinforcement. Skilled persons know how to evaluate this quantity empirically or analytically based on the type of fibers and resin used.

When $ST_{rt} > ST_{rt}$ Allowable

Compute

$Mr' = ST_{rt}$ Allowable $\cdot Mr/ST_{rt}$

Compression Zone

$ST_{rc} < ST_{rc}$ Allowable

$ST_{rc} = (C/(a \cdot b)) \cdot n"$

Where

ST_{rc} = Axial compressive stress in compression reinforcement

ST_{rc} Allowable = Allowable axial compressive stress in compression reinforcement. Skilled persons know how to evaluate this quantity empirically or analytically based on the type of fibers and resin used.

When $ST_{rc} > ST_{rc}$ Allowable compute

$Mr' = ST_{rc}$ Allowable $\cdot Mr/ST_{rc}$

When $M_r' > 0.9 \cdot \{\text{Maximum Load Moment}\}$ then process 50 goes to block 87. Otherwise, the process 50 proceeds to block 88.

Process block 87 indicates that whenever the tension reinforcement 28 or compression reinforcement 29 is not substantially capable of bearing the tensile or compressive stress respectively corresponding to load 16, whichever reinforcement is too weak, increased from the set of working reinforcements, 20% of the depth of the member is removed and process block 87 returns to process block 58 to determine whether the now lighter member is strong enough with the added reinforcement but reduced wood.

Fire Resistance Rating

Decision block 88 determines whether the member meets the fire resistance rating. If it does not, the method progresses to process block 89, which adds width to the member and returns to block 88 for another test according to the following equations. These equations, however, only apply, and, moreover, fire ratings may only be obtained for reinforced members in which the reinforcements exclusively contain carbon, fiberglass or aramid fibers. When aramid fibers are used a factor of 0,7 should be inserted into the equations below. Also, the reinforcement must be adhered between two laminae rather than on an extension surface of the member.

1.5" Wide

$FRR_r = .25 \cdot 2.54 \cdot z \cdot b \cdot (4 - 2\ (b/d))$ exposed to fire on four sides

$FRR_r = .25 \cdot 2.54 \cdot z \cdot b \cdot (4 - (b/d))$ exposed to fire on three sides

NOTE: Formulas for use in assemblies only. Multiply by .75 for single members.

2.5" Wide

$FRR_r = .4 \cdot 2.54 \cdot z \cdot b \cdot (4 - 2\ (b/d))$ exposed to fire on four sides

$FRR_r = .4 \cdot 2.54 \cdot z \cdot b \cdot (4 - (b/d))$ exposed to fire on three sides

NOTE: Formulas for use with single members. For assemblies multiply by 1.1.

3-1/8" and 5-1/8" Wide

$FRR_r = .60 \cdot 2.54 \cdot z \cdot b \cdot (4 - 2\ (b/d))$ exposed to fire on four sides

$FRR_r = .60 \cdot 2.54 \cdot z \cdot b \cdot (4 - (b/d))$ exposed to fire on three sides

NOTE: Formulas for use with single members. For assemblies multiply by 1.1.

6.75" Wide and Greater

$FRR_r = 2.54 \cdot z \cdot b \cdot (4 - 2\ (b/d))$ exposed to fire on four sides

$FRR_r = 2.54 \cdot z \cdot b \cdot (4 - (b/d))$ exposed to fire on three sides

Where

FRR_r = Fire resistance rating of FiRP™ Glulams

z = Load factor (NER-250)

Process block 90 indicates that process 50 is complete and wood structural member 10 may be manufactured according to the depth, width, and tension reinforcement obtained from the set of working depths, widths, and reinforcement.

It will be obvious to those having skill in the art that many changes may be made to the details of the above-described embodiment of this invention without departing from the underlying principles thereof. The scope of the present invention should be determined, therefore, only by the following claims.

Claims

1. A wood structural member for bearing a predetermined load along a first axis and having a depth along said first axis, a length along a longitudinal axis transverse to said first axis, and a width along a second axis transverse to said first and longitudinal axes, said predetermined load producing compressive and tensile stresses in said member in respective compression and tension portions on opposite sides of a neutral axis, said member comprising:

a plurality of wood laminae, made of wood of a predetermined variety and grade, bonded together;

at least one synthetic tension reinforcement having a length aligned with said longitudinal axis of said member and having plural fiber strands held within a resin matrix, said reinforcement or reinforcements each being adhered to at least one predetermined surface of a predetermined wood segment of said structural member; and

wherein said width and depth of said member and the modulus of elasticity, length, and strength of each said synthetic reinforcement have been selected to prevent said predetermined load from creating a compressive stress in said wood laminae of said compression portion from exceeding a predetermined level.

2. The member of claim 1 in which each of said synthetic reinforcements has a length and in which one of said synthetic reinforcements is placed in said tension zone and in which said length of said synthetic reinforcement is selected to prevent said load from creating a stress in any portion of the extreme fiber of the tension zone that exceeds a predetermined maximum level.

3. The member of claim 1 in which said width and depth of said structural member and said modulus of elasticity, length, and strength of each said synthetic reinforcement have been selected so that the member will have greater than a predetermined stiffness.

4. The member of claim 1 in which the width and depth of the structural member and said modulus of elasticity, length, and strength of said synthetic reinforcement have been selected so that said member will have greater than a predetermined shear strength.

5. The member of claim 1 in which said width and depth of said structural member and said modulus of elasticity, length, and strength of said synthetic reinforcement have been selected so that the member will be able to resist a predetermined level of bending and axially compressive force.

6. The member of claim 1 in which said width and depth of said structural member and said modulus of elasticity, length, and strength of said synthetic reinforcement have been selected so that said member will have a predetermined ability to resist a combination of bending and axial tensile force.

7. The member of claim 1 in which said width and depth of said structural member and the modulus of elasticity, length, and strength of said synthetic reinforcement have been selected so that said depth of said member does not exceed a predetermined maximum.

8. The member of claim 1 in which said width and depth of said structural member and the modulus of elasticity, length, and strength of said synthetic reinforcement have been selected so that said width of said member does not exceed a predetermined maximum.

9. The member of claim 1 comprising a lowermost lamina having a lowermost surface, said synthetic

reinforcement being adhered to said lowermost side of the lowermost lamina.

10. The member of claim 1 in which said depth and said width of said member and the elasticity of said synthetic reinforcement are chosen so that said compressive stress caused by said load in said compression portion of said structural member is greater than a predetermined minimum.

11. A wood structural member for bearing a predetermined load along a first axis and having a depth along said first axis, a length along a longitudinal axis transverse to said first axis, and a width along a second axis transverse to said first and longitudinal axes, said predetermined load producing compressive and tensile stresses in said member in respective compression and tension portions on opposite sides of a neutral axis, said member comprising:

a plurality of wood laminae, made of wood of a predetermined variety and grade, bonded together, wherein each wood laminae is made of at least two segments of wood bonded together with finger joints;

at least one synthetic tension reinforcement having a length aligned with said longitudinal axis of said member and having plural fiber strands held within a resin matrix, said reinforcement or reinforcements each being adhered to at least one predetermined surface of a predetermined wood segment of said structural member; and

wherein said width and depth of said member and said modulus of elasticity, length and strength of each said synthetic reinforcement have been selected to prevent said failure of any of said finger joints.

12. A method of constructing a wood structural member for bearing a predetermined load along a first axis and having a depth along said first axis, a length along a longitudinal axis transverse to said first axis, a width

along a second axis transverse to said first and longitudinal axes, plural wood laminae bonded together, a synthetic tension reinforcement of predetermined length and composition adhesively attached at a predetermined depth in said member and in which said predetermined load creates compressive and tensile stresses in said structural member in respective compression and tension portions on opposite sides of a neutral axis, said method comprising the steps of:

calculating a depth and width for said member and a thickness for said tension reinforcement that prevents said compressive stress created in said compression portion from exceeding a predetermined level and that allows said tension reinforcement to withstand said tensile force; and

constructing a beam having said calculated depth and width and further having a tension reinforcement of said predetermined composition and positioned at said predetermined depth and having said calculated thickness.

13. The method of claim 12 in which said tension reinforcement is comprised of at least two layers of resin encased fibers, the layers adhesively bonded together.

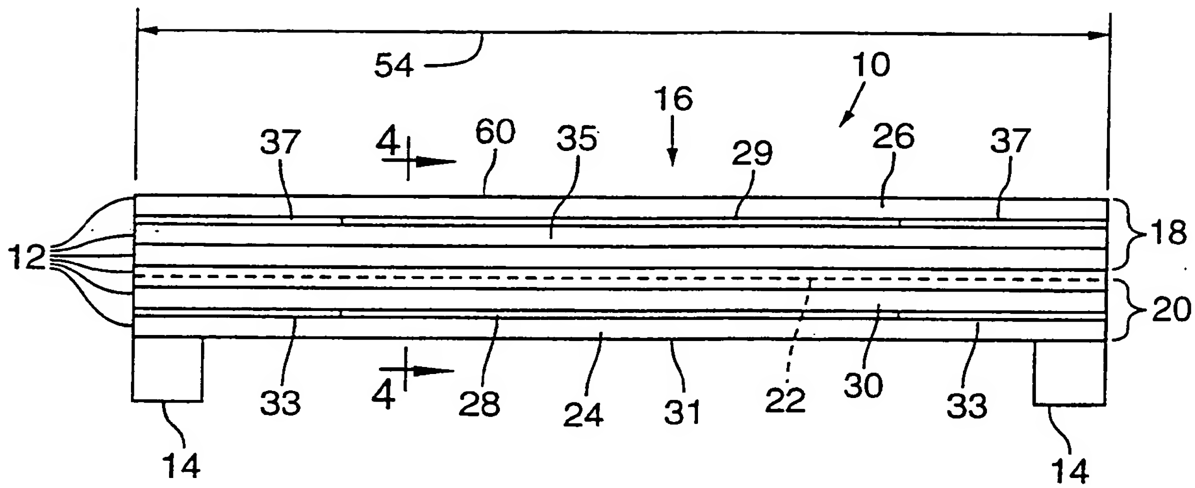
14. The method of claim 12 in which the depth and the width of said member and the elasticity of said synthetic reinforcement are chosen so that said compressive stress caused by said load in said compression portion of said structural member is greater than a predetermined minimum.

15. The method of claim 12 in which the depth and width of said member and said elasticity and strength of said tension reinforcement are selected to prevent a predetermined shear stress from causing said member to fail.

16. The method of claim 12 in which said depth

and width of the member and the elasticity and strength of the tension reinforcement are selected to create a member having a predetermined stiffness.

FIG. 1


54
10
16
37
4
60
35
29
26
37
12
18
20
33
4
28
24
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30
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14
14

FIG. 2

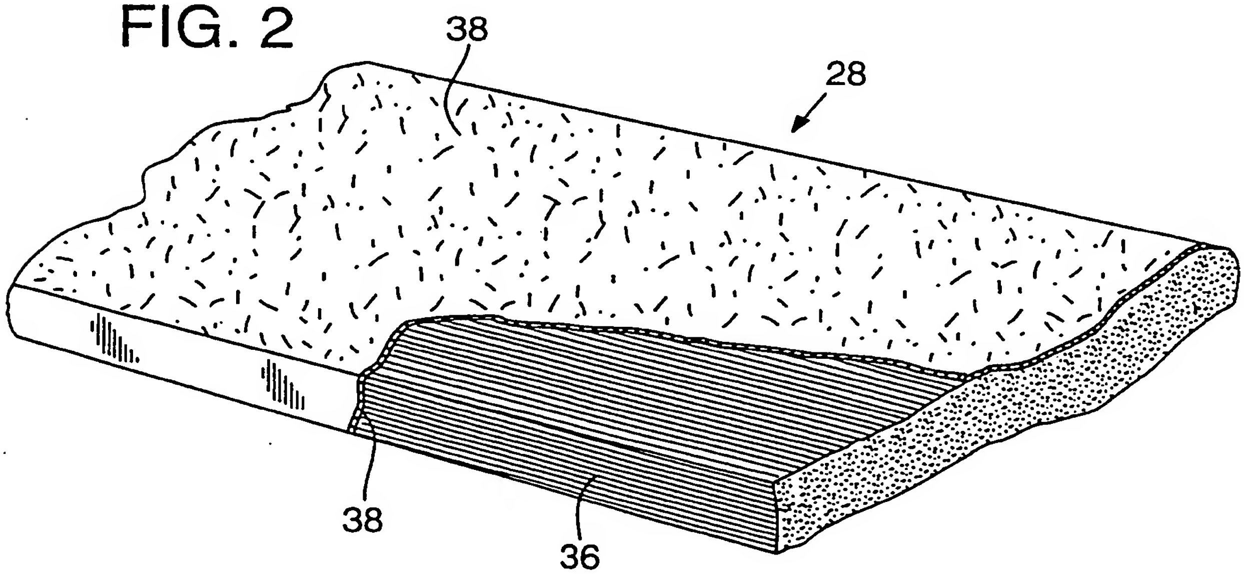

38
28
38
36

FIG. 3–1

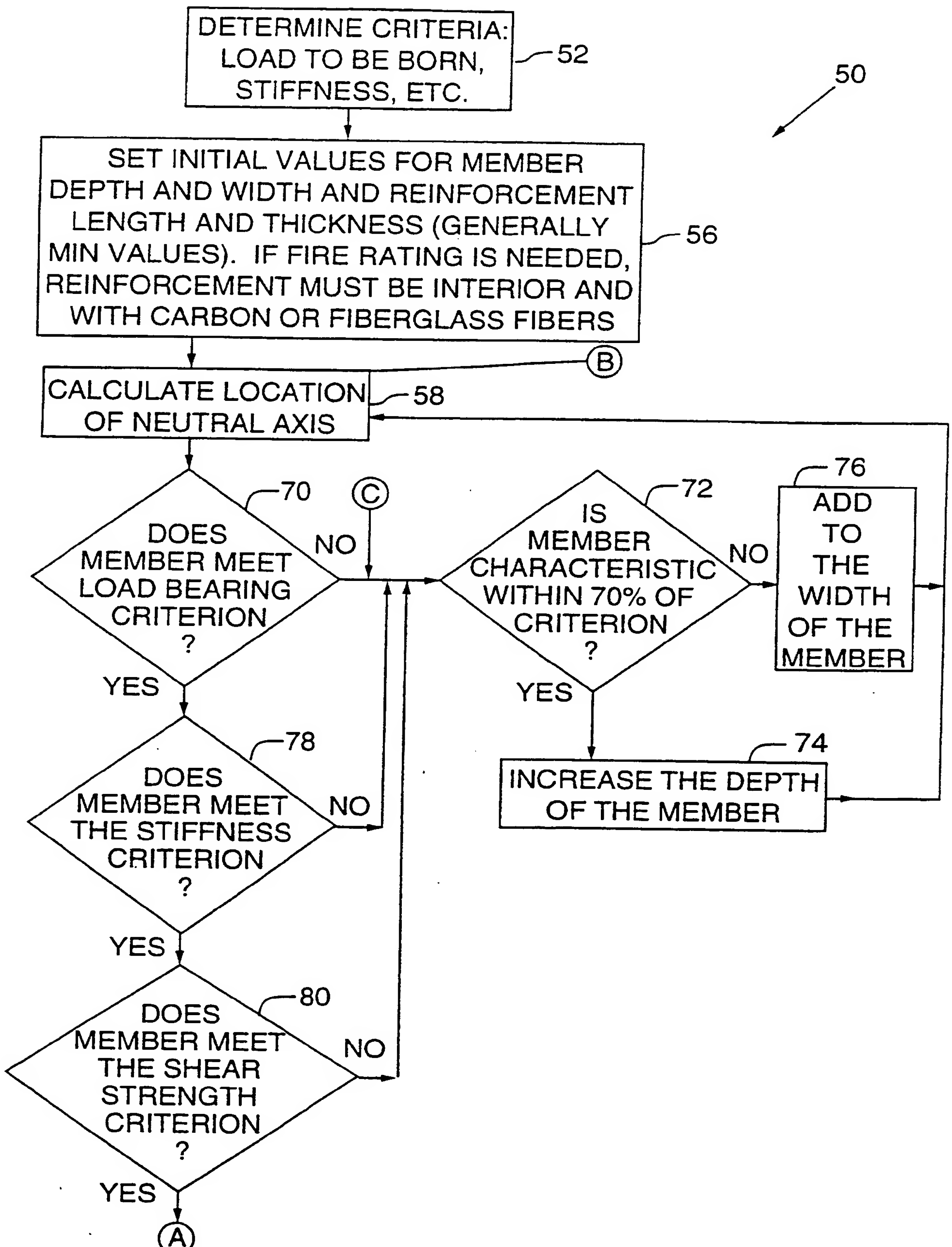

DETERMINE CRITERIA: LOAD TO BE BORN, STIFFNESS, ETC.
52
50
SET INITIAL VALUES FOR MEMBER DEPTH AND WIDTH AND REINFORCEMENT LENGTH AND THICKNESS (GENERALLY MIN VALUES). IF FIRE RATING IS NEEDED, REINFORCEMENT MUST BE INTERIOR AND WITH CARBON OR FIBERGLASS FIBERS
56
B
CALCULATE LOCATION OF NEUTRAL AXIS
58
DOES MEMBER MEET LOAD BEARING CRITERION ?
70
C
NO
YES
IS MEMBER CHARACTERISTIC WITHIN 70% OF CRITERION ?
72
NO
YES
ADD TO THE WIDTH OF THE MEMBER
76
INCREASE THE DEPTH OF THE MEMBER
74
DOES MEMBER MEET THE STIFFNESS CRITERION ?
78
NO
YES
DOES MEMBER MEET THE SHEAR STRENGTH CRITERION ?
80
NO
YES
A

FIG. 3–2

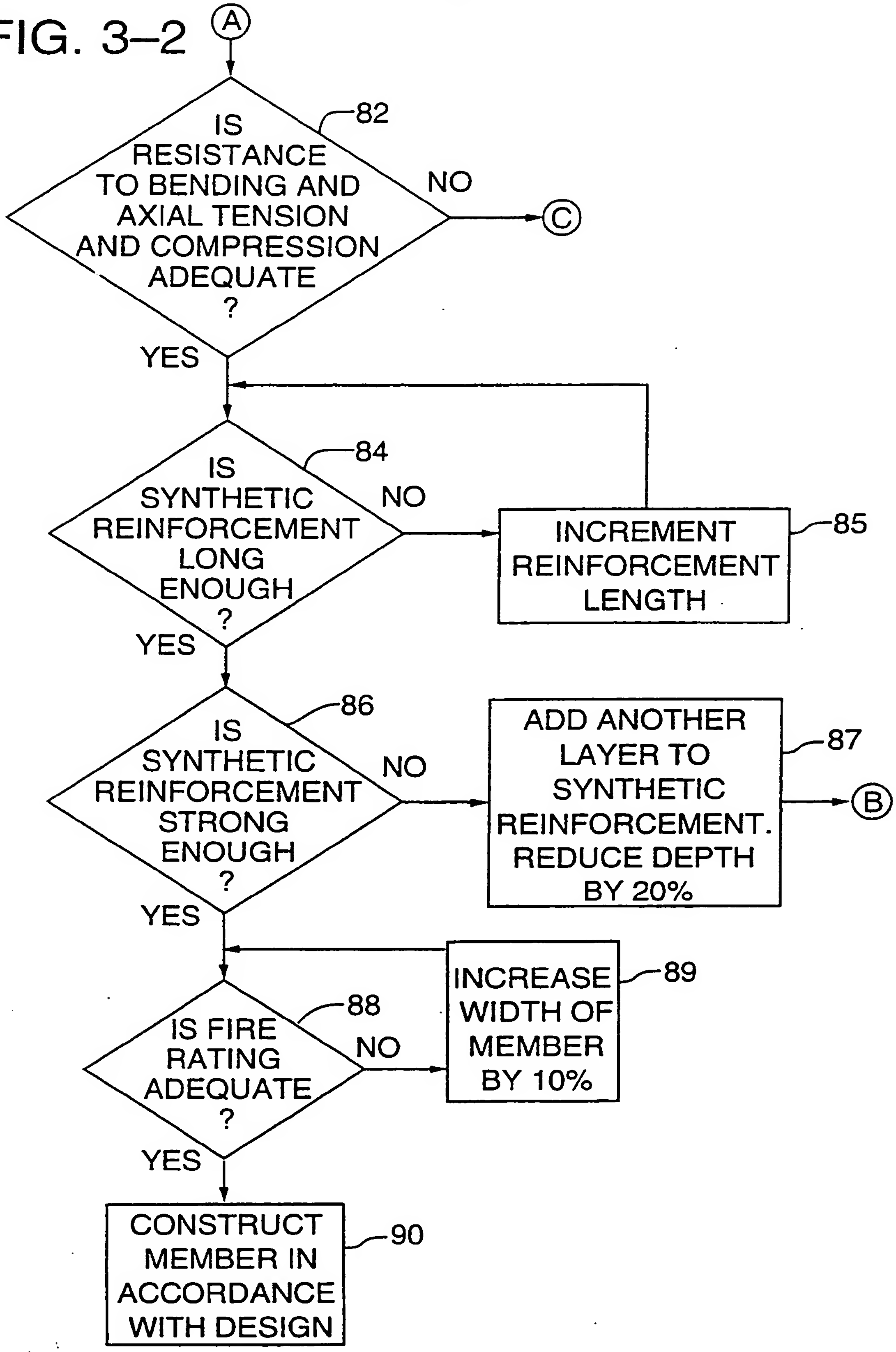
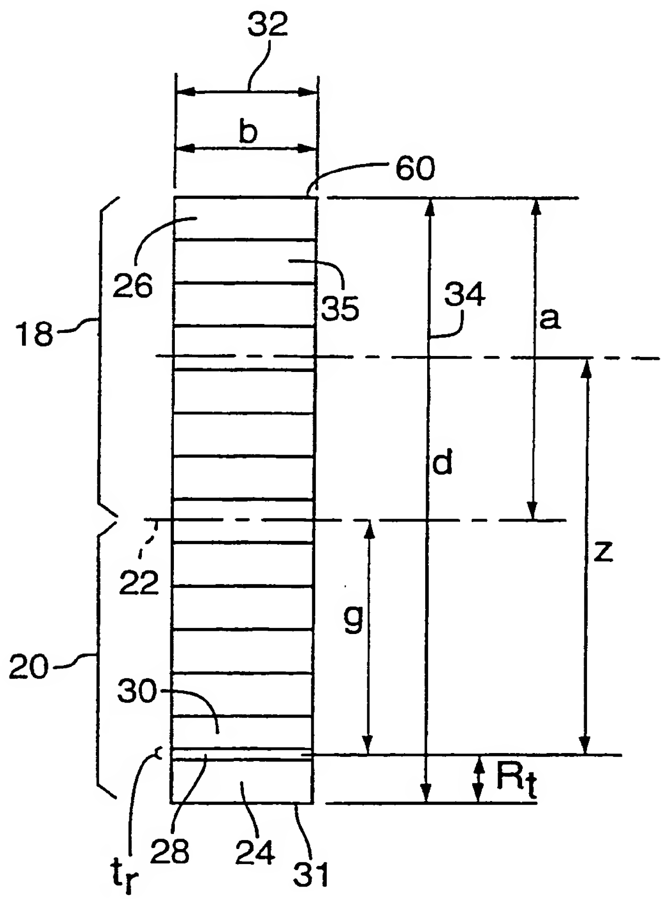

A
IS RESISTANCE TO BENDING AND AXIAL TENSION AND COMPRESSION ADEQUATE ?
82
NO
C
YES
IS SYNTHETIC REINFORCEMENT LONG ENOUGH ?
84
NO
INCREMENT REINFORCEMENT LENGTH
85
YES
IS SYNTHETIC REINFORCEMENT STRONG ENOUGH ?
86
NO
ADD ANOTHER LAYER TO SYNTHETIC REINFORCEMENT. REDUCE DEPTH BY 20%
87
B
YES
IS FIRE RATING ADEQUATE ?
88
NO
INCREASE WIDTH OF MEMBER BY 10%
89
YES
CONSTRUCT MEMBER IN ACCORDANCE WITH DESIGN
90

FIG. 4



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US95/08329

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :B32B 5/08, 5/16; E04C 3/26, 3/29
US CL :Please See Extra Sheet.
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 52/309.16, 727, 730.1; 156/630, 632; 264/229, 231; 428/96, 114, 294

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X, O	Proceedings of the 1991 International Timber Engineering Conference, Volume 3, 02-05 September 1991, J. W. G. Van De Kuilen, "Theoretical and Experimental Research on Glass Fibre Reinforced Laminated Timber Beams", pages 3.226-3.233, see entire document.	1-16

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 AUGUST 1995	11 SEP 1995

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	BLAINE R. COPENHEAVER
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